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HEMODYNAMICS IN PATIENT-SPECIFIC CORONARY ARTERIES CONSIDERING BLOOD ELASTIC BEHAVIOR: NUMERICAL STUDY

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ABSTRACT

The present study emphasises the importance of the blood elastic property in the hemodynamics of patient-specific left coronary arteries. An In-House OpenFOAM® code was developed to take into account the blood flow as real as possible. At systolic peak, highest inlet velocity, differences in the velocity profiles are observed, considering Multi-mode PTT model (shear-thinning and blood elastic effects) or Carreau model (only shear-thinning effect). In arteries with small diameter, as coronary arteries, the elastic blood behavior has an important role on the blood flow pattern.

Keywords: blood elastic property, hemodynamics, coronary artery, Multi-mode PTT model, OpenFOAM®.

INTRODUCTION

Cardiovascular diseases are, nowadays, one of the main causes of death, in humans, in developed countries (Mozaffarian *et al*., 2015). The clinical practice shows that specific sites in human circulatory system are sensitive to atherosclerosis development. The artery narrows due to the accumulation of lipoproteins inside the artery and near the wall. The medical scans, provided by the hospitals, give information about the geometry and the location of atherosclerosis disease. However, the images do not explain the hemodynamics which numerical simulations can describe in detail. Numerical studies have gained importance as an auxiliary tool for the prevention and treatment of such diseases. In the literature (Alastruey *et al*., 2011, van der Giessen *et al*., 2011, Chaichana *et al*., 2013), numerical studies of left coronary arteries (LCA) do not consider, simultaneously, all the blood properties: elastic property of blood, shear-thinning blood behavior, pulsatile flow, fluid-structure interaction. The present work presents an In-House developed software which simulates, as real as possible, the blood flow. A constitutive equation model, Phan-Thien-Tanner (PTT) Model, taking into account the blood elastic behavior, was implemented in OpenFOAM® code and validated. The goal of the paper is to conclude about the importance of considering the blood elastic property in the hemodynamics of patient-specific left coronary arteries.

NUMERICAL MODEL

A patient-specific LCA geometry is represented in Figure 1: a healthy artery with diameter equal to 3.6 mm at the inlet. The 3D geometry was created in MIMICS® software and, then, imported to ANSYS® to generate a refined tetrahedral mesh. The mesh was then supplied to OpenFOAM® for numerical simulations.

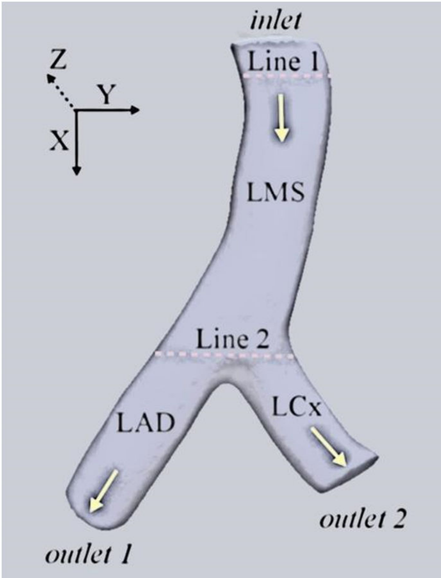

Fig. 1 - 3D representation of a patient-specific left conorary artery (LCA).Left Main Steam (LMS), Left Anterior Descending Artery (LAD) and Left Circumflex Artery (LCx) of the LCA.

In the open source code OpenFOAM®, the constitutive equation, describing the blood rheology, was implemented, and à posteriori solved, simultaneously, with the conservative equations.

The mass and momentum conservative equations are:

$$\nabla \cdot (\mathbf{U}) = 0 \tag{1}$$

$$\frac{\partial(\rho \mathbf{U})}{\partial t} + \nabla \cdot (\rho \mathbf{U}.\mathbf{U}) = -\nabla \mathbf{p} + \nabla \cdot \boldsymbol{\tau}_\mathbf{S} + \nabla \cdot \boldsymbol{\tau}_\mathbf{P} \tag{2}$$

$\mathbf{U}$ is the velocity vector, ρ the mean density and $\boldsymbol{\tau}_\mathbf{S}$ the stress tensor of the solvent part defined by:

$$\boldsymbol{\tau}_\mathbf{S} = 2\eta_S \mathbf{D} \tag{3}$$

where η_S is the solvent viscosity and $\mathbf{D}$ the deformation rate tensor:

$$\mathbf{D} = \frac{1}{2}\left(\nabla \mathbf{U} + [\nabla \mathbf{U}]^T\right) \tag{4}$$

The stress tensor of the polymeric part, $\boldsymbol{\tau}_\mathbf{P}$, is well-defined by a constitutive equation. Several constitutive equations, demonstrating the elastic behavior of a fluid, are cited in the literature (Favero, 2009): Oldroyd-B, Giesekus, FENE (Finite Extensible Nonlinear Elastic), PTT (Phan-Thien-Tanner) linear, exponential or multi-mode, DCPP (Double Convected Pom-Pom), etc. The one chosen and implemented in the OpenFOAM® code was the Multi-mode PTT model. The respective parameters for blood at 37 ºC are well defined by Campo-Deaño *et al*. (2013).

Pulsatile blood flow was considered and is represented in Figure 2 for three cardiac cycles. The systolic peak (maximum velocity in the cardiac cycle) can be observed.

As Dong *et al*. (2015), the time-dependent velocity and pressure profiles of physiological pulsatile flow and pressure waveforms were assembled using Fourier series in Matlab® software (MathWorks Inc, Moler, Massachusetts, USA).

A time-dependent and radius-dependent inlet velocity profile was imposed in order to be instantaneously fully developed. A time-dependent and constant-radius pressure wave was imposed at the outlet branches.

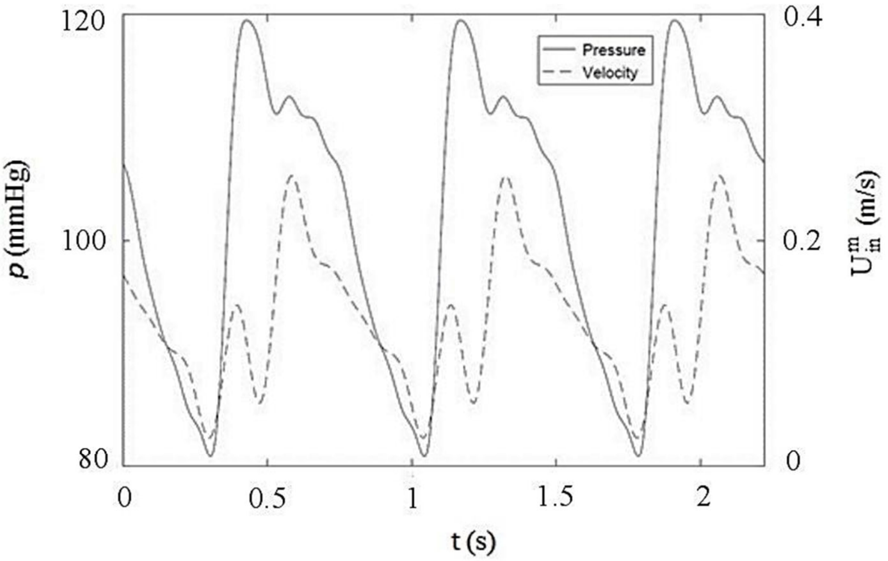

Fig. 2 - Mean inlet velocity profile, U_{in}^{m} , and outlet pressure profile, *p*, throughout three cardiac cycles.

RESULTS AND CONCLUSIONS

Velocity fields at systole peak, maximum velocity of the cardiac cycle, considering elastic behavior of blood (Multi-mode PTT Model) and without elastic behavior (Carreau Model) are represented in Figure 3 (middle plane representation of the 3D coronary artery).

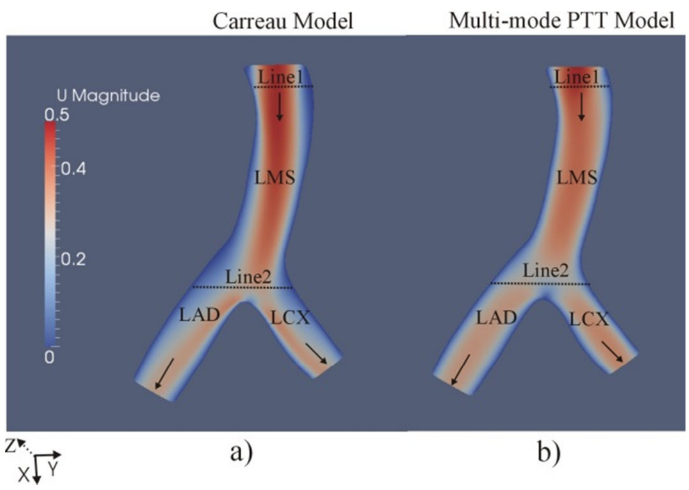

Fig. 3 - Velocity field U (m/s) at systolic peak considering a) Carreau Model (only shear-thinning blood behavior; b) Multi-mode PTT Model (shear thinning and elastic blood behavior).

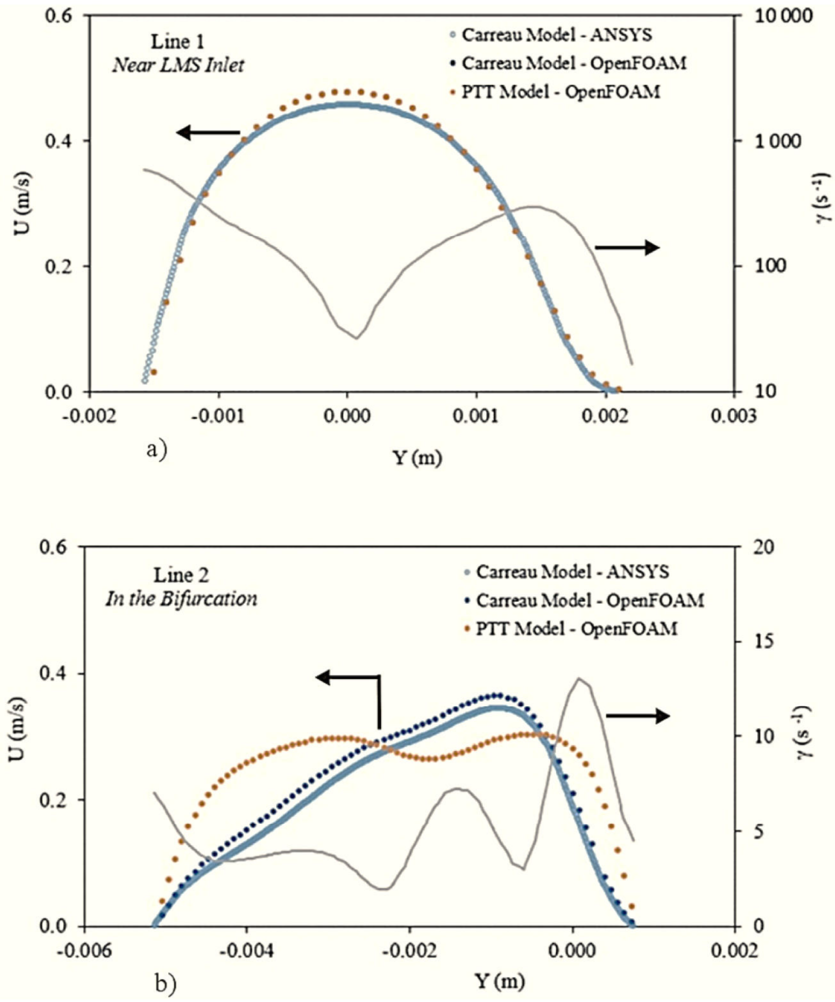

Fig. 4 - Velocity profiles U (m/s) and Shear Stress (γ) along Y Coordinate (m) near the LMS inlet and in the bifurcation region.

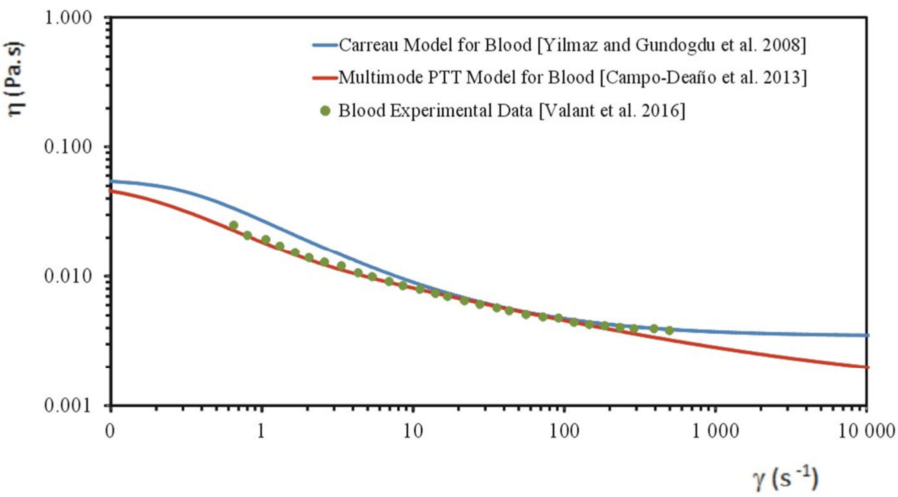

Fig 5 - Apparent viscosity (η) vs. Shear Rate (γ) using Carreau model for blood rheology (Yilmaz and Gundoglu *et al*., 2008), Multi-mode PPT model (Campo-Deaño *et al*., 2013) and blood experimental data (Valant *et al*., 2016).

Near the LMS inlet (Line 1 of Figure 3), the velocity profiles, taking into account the Multi-mode PTT model or Carreau model, are similar. The inlet pulsatile flow is the same for both cases and the effect of blood elastic behavior is not developed at this location. The shear stress values are in the range [17-597] s^{-1} (Figure 4a). In this range, both Carreau and Multi-mode PTT models fit well blood experimental data (Figure5).

In the bifurcation region (Line 2 of Figure 3), different profiles are observed concerning Multi-mode PTT or Carreau model. The differences are due to the elastic behavior of blood in small arteries where shear rate presents low values. Shear rate values are in the range of [1.9-13] s^{-1}(Figure 4b). For this range, Multi-mode PTT model fits quite well blood experimental data while deviations are observed for Carreau Model (Figure 5).

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